AQUACULTURE EXTENSION
Illinois ~ Indiana Sea Grant Program

Sea Grant # IL-IN-SG-97-2

Fact Sheet AS-503

WATER QUALITY

A Fish Farmer's Guide to Understanding Water Quality

LaDon Swann, *Department of Animal Sciences*
Illinois-Indiana Sea Grant Program
Purdue University

To help the fish farmer better understand the properties of water as they affect fish culture, the following subjects will be covered in this fact sheet:

- Physical Characteristics of Water
- Water Balance in Fish
- Sources of Water
- Water Quantity
- Water's Physical Factors
- Water's Chemical Factors

Introduction

Importance of Water Quality in Aquaculture

Fish perform all their bodily functions in water. Because fish are totally dependent upon water to breathe, feed, grow, excrete wastes, maintain a salt balance, and reproduce, understanding the physical and chemical qualities of water is critical to successful aquaculture. To a great extent, water determines the success or failure of an aquaculture operation.

Physical Characteristics of Water

Water can hold large amounts of heat with a relatively small change in temperature. This heat capacity has far reaching implications. It permits a body of water to act as a buffer against wide fluctuations in temperature. The larger the body of water, the slower the rate of temperature change. Furthermore, aquatic organisms take on the temperature of their environment and cannot tolerate rapid changes in temperature.

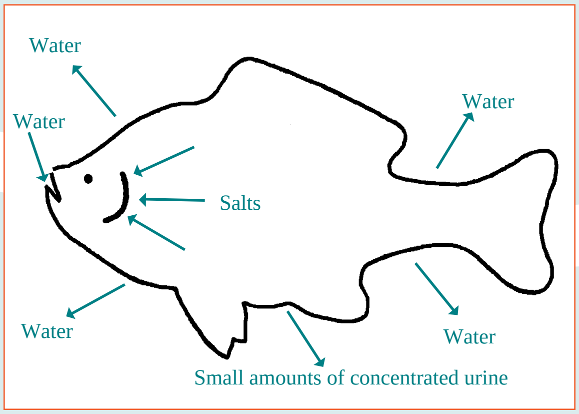
Water has very unique density qualities. Most liquids become denser as they become cooler. Water, however, gets denser as it cools until it reaches a temperature of approximately 39°F. As it cools below this point, it becomes lighter until it freezes (32°F). As ice develops,water increases in volume by 11 percent. The increase in volume allows ice to float rather than sink, a characteristic that prevents ponds from freezing solid.

Far from being a "universal solvent," as it is sometimes called, water can dissolve more substances than any other liquid. Over 50 percent of the known chemical elements have been found in natural waters, and it is probable that traces of most others can be found in lakes, streams, estuaries, or oceans.

Water Balance in Fish

The elimination of most nitrogen waste products in land animals is performed through the kidneys. In contrast, fish rely heavily on their gills for this function, excreting primarily ammonia. A fish's gills are permeable to water and salts. In the ocean, the salinity of water is more concentrated than that of the fish's body fluids. In this environment water is drawn out, but salts tend to diffuse inward. Hence, marine fishes drink large amounts of sea water and excrete small amounts of highly salt-concentrated urine (Figure 1).

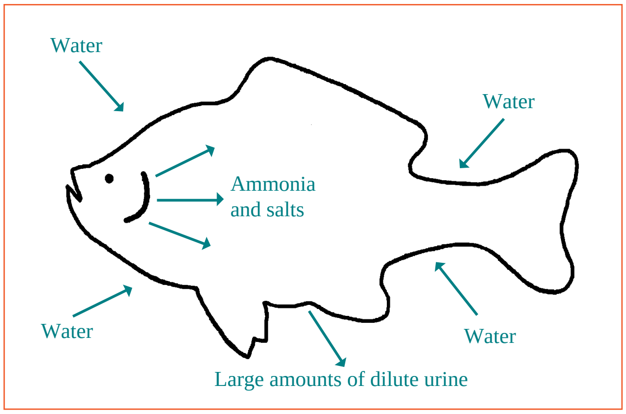
Figure 1. Direction of water, ammonia, and salt movements into and out of saltwater fish. Saltwater fish drink large amounts of water and excrete small amounts of concentrated urine.



This publication can be found on the Web: http://www.ansc.purdue.edu/aquanic

In fresh-water fish, water regulation is the reverse of marine species. Salt is constantly being lost through the gills, and large amounts of water enter through the fish's skin and gills (Figure 2). This is because the salt concentration in a fish (approximately 0.5 percent) is higher than the salt concentration of the water in which it lives. Because the fish's body is constantly struggling to prevent the "diffusion" of water into its body, large amounts of water are excreted by the kidneys. As a result, the salt concentration of the urine is very low. By understanding the need to maintain a water balance in freshwater fish, one can understand why using salt during transport is beneficial to fish.

Figure 2. Direction of water, ammonia, and salt movement into and out of freshwater fish. Freshwater fish do not drink water, but excrete large amounts of dilute urine.



Sources of Water

Water is always a limiting factor in commercial fish production. Many of the negative chemical and environmental factors associated with most operations have their origins in the source of water selected. Final site selection has to be made based on both the quality and quantity of water available. The most common sources of water used for aquaculture are wells, springs, rivers and lakes, groundwater, and municipal water. Of the sources mentioned, wells and springs are considered consistently high quality sources (see AS-486 for more information on water sources).

Water Quantity

The beginning aquaculturist usually underestimates the quantity of water required for commercial production. **It is generally accepted that a minimum rate of 13 gallons per minute (gpm) is required for each surface acre of ponds**. With this in mind, a 100-acre fish farm will need to have wells capable of producing 1,300 gpm of water. Such large volumes are required to replace water lost to evaporation and seepage. In addition, the farmer may have several ponds to fill quickly during the spawning season. **In raceway culture, it is advisable to have a minimum flow rate of 500 gpm.** Even water recirculating systems that recycle water require large quantities of water. If a 100,000 gallon capacity water recirculating operation exchanges 10 percent of the water daily, it will require 10,000 gallons of water per day.

The availability of subsurface groundwater in Indiana and Illinois varies widely, ranging from as little as 10 gpm or less to over 2,000 gpm from properly constructed, large diameter wells. With the exception of the aquifers located along major river drainages (usually high yields), potential yields are divided into three distinct regions:

1) Northern Indiana and Illinois are good to excellent and, exclusive of some areas near northwestern Indiana, yields from 200-2,000 gpm can be expected.

2) In the central portion of Indiana and Illinois, groundwater conditions range from fair to good. Well yields from 100-400 gpm are typical for many large-diameter wells.

3) Many areas of southern Indiana and Illinois lack ground-water; generally, less than 10 gpm are available from properly constructed wells. In these areas, the major sources of groundwater are present in the sand and gravel deposits of the river valley aquifers.

These yield potentials do not indicate that an unlimited number of wells can be developed in given location. Detailed studies, including exploratory drilling and test pumping, should be conducted to adequately evaluate the groundwater resource in any given area. The resultant change in the water table is produced by spheres of influence from nearby wells.

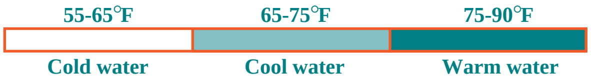
Water's Physical Factors

Temperature

After oxygen, water temperature may be the single most important factor affecting the welfare of fish. Fish are cold-blooded organisms and assume approximately the same temperature as their surroundings. The temperature of the water affects the activity, behavior, feeding, growth, and reproduction of all fishes. Metabolic rates in fish double for each 18°F rise in temperature.

Fish are generally categorized into warm water, cool water, and cold water species based on optimal growth temperatures (Figure 3).

Figure 3. General temperature ranges for cold water, cool water, and warm water species.



Channel catfish and tilapia are examples of warm water species. Their temperature range for growth is between 75-90°F. A temperature of 85°F for catfish and 87°F for tilapia is considered optimum.

Walleye and yellow perch are examples of cool water species. Ranges for optimum growth fall between 60° and 85°F. Temperatures in the upper end of this range are considered best for maximum growth for most cool water species.

Cold water species include all species of salmon and trout. The most commonly cultured cold water species in the Midwest is rainbow trout, whose optimal temperature range for growth is 48-65°F.

Ideally, species selection should be based in part on the temperature of the water supply. Any attempt to match a fish with less than ideal temperatures will involve energy expenditures for heating or cooling. This added expense will subsequently increase production costs.

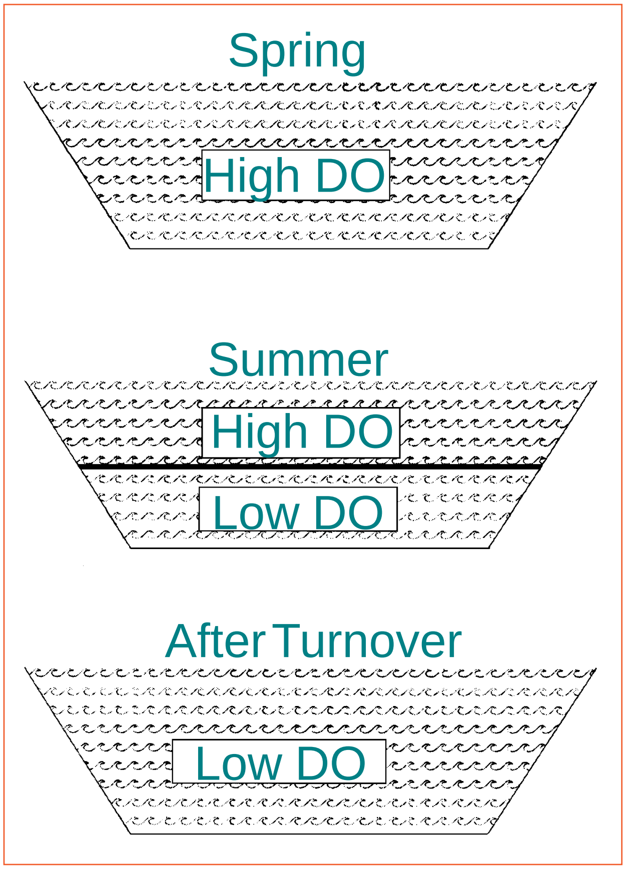
Temperature also determines the amount of dissolved gases (oxygen, carbon dioxide, nitrogen, etc.) in the water. The cooler the water the more soluble the gas. Temperature plays a major role in the physical process called thermal stratification (Figure 4). As mentioned earlier, water has a high-heat capacity and unique density qualities. Water has its maximum density at 39.2°F. In spring, water temperatures are nearly equal at all pond depths. As a result, nutrients, dissolved gases, and fish wastes are evenly mixed throughout the pond. As the days become warmer, the surface water becomes warmer and lighter while the cooler-denser water forms a layer underneath.

Circulation of the colder bottom water is prevented because of the different densities between the two layers of water. Dissolved oxygen levels decrease in the bottom layer since photosynthesis and contact with the air is reduced. The already low oxygen levels are further reduced through decomposition of waste products, which settle to the pond bottom. Localized dissolved oxygen depletion poses a very real problem to the fish farmer.

Summer stratification is a greater problem for fish raised in deeper farm ponds. Stratification may last for several weeks. This condition may develop into a major fish kill when sudden summer rains occur. These rains will cool the warmer upper layer of water enough to allow it to mix with the oxygen poor layer below. Decomposing materials in the oxygen-poor layer are again mixed evenly throughout the pond, resulting in an overall reduction in the dissolved oxygen level. Fish previously able to avoid the oxygen depleted layer are now susceptible to low-dissolved oxygen syndrome and possibly death.

Ice is another physical factor directly related to temperature. Normally, ice cover does not impede photosynthesis. Fish consume less oxygen at colder temperatures, greatly reducing the overall oxygen demand. But fish can still suffer from low-dissolved oxygen under snow covered ice. Under extended ice cover, other gases (carbon dioxide, hydrogen sulfide, methane, etc.) can build up to dangerously high levels. Mechanical aeration is probably the most reliable way of preventing an ice buildup by keeping large areas of the pond free of ice.

Figure 4. This is an illustration of seasonal changes of water temperatures which occur in fish ponds. In spring, temperatures and dissolved oxygen are uniform throughout the pond. During the summer, stratification may occur and create an upper layer of water with high-dissolved oxygen and lower layer with low-dissolved oxygen. After a rain or when a phytoplankton die-off occurs the water may turnover.



Suspended Solids

Suspended solids is a term usually associated with plankton, fish wastes, uneaten fish feeds, or clay particles suspended in the water. Suspended solids are large particles which usually settle out of standing water through time. Large clay particles are an exception. Clay particles (which will be discussed again) are kept in suspension because of the negative electrical charges associated with them.

Plankton

Turbidity caused by phytoplankton (microscopic plants) and zooplankton (microscopic animals) is not directly harmful to fish. Phytoplankton (green algae) not only produces oxygen, but also provides a food source for zooplankton and filter feeding fish/shellfish. Phytoplankton also uses ammonia produced by fish as a nutrient source. Zooplankton is a very important food source for fry and fingerlings such as hybrid striped bass and yellow perch. However, excessive amounts of algae can lead to increased rates of respiration during the night thereby consuming extra oxygen. Excessive phytoplankton buildups or "blooms" which subsequently die will also consume extra oxygen. Any wide swings between day and night oxygen levels can lead to dangerously low oxygen concentrations.

Fish Wastes

Suspended fish wastes are a serious concern for water recirculating culture systems. Large amounts of suspended and settleable solids are produced during fish production. As a rule, one pound of fish waste is produced for every pound of fish produced. Fish waste particles can be a major source of poor water quality because they may contain up to 70 percent of the nitrogen load in the system. These wastes not only irritate the fish's gills, but can cause several problems to the biological filter. The particulate waste can clog the biological filter, causing the nitrifying bacteria to die from lack of oxygen. Particulate waste can also promote the growth of bacteria that produces—rather than consumes ammonia.

Clay

Most clay turbidity problems are the result of exposed soil on the pond levee, exposed watershed, crayfish activity, or feeding of bottom dwelling species such as carp and catfish. Turbidity levels exceeding 20,000 ppm can cause behavioral changes in fish. In natural bodies of water, turbidity values seldom exceed these critical levels. Even "muddy looking" ponds rarely have concentrations greater than 2,000 ppm.

Turbidity caused by clay or soil particles, however, can restrict light penetration and limit photosynthesis. Sedimentation of soil particles may also smother fish eggs and destroy beneficial communities of bottom organisms such as bacteria.

Removal of clay turbidity can be accomplished by adding materials that attach to the negative charges of the clay particles, forming particles heavy enough to settle to the bottom. Common remedies for clay turbidity are 7-10 square bales of hay per surface acre, or 300-500 pounds of gypsum per surface acre. Gypsum applications may be repeated at two week intervals if ponds do not clear.

Water's Chemical Factors

Photosynthesis

Photosynthesis is one of the most important biological activities in standing pond aquaculture. Many water quality parameters such as dissolved oxygen, carbon dioxide, pH cycles, nitrogenous waste products are regulated by the photosynthetic reaction in phytoplankton. **Simply stated, photosynthesis is the process by which phytoplankton uses sunlight to convert carbon dioxide into a food source and to release oxygen as a by-product (Figure 5).**

Figure 5. Equation illustrating the photosynthetic process which occurs in fish ponds and produces food for phytoplankton and releases oxygen as a by-product.

$$\text{Chlorophyll of Plants + Carbon Dioxide} \xrightarrow{\text{Sunlight}} \text{food + oxygen}$$

In addition to supplying oxygen in fish ponds, photosynthesis also removes several forms of nitrogenous wastes, such as ammonia, nitrates, and urea.

The phytoplanktonic plant pigments involved in this chemical reaction are referred to as chlorophyll. These are the same pigments found in higher plants such as tree leaves.

Because the photosynthetic process is driven by sunlight, greatest concentrations of oxygen occur when the sun is highest on the horizon (usually 2-3 p.m. in the afternoon). At night, photosynthesis ceases and the phytoplankton primarily respirate.

Respiration is the reverse of photosynthesis in that oxygen is used by phytoplankton to convert food to energy and carbon dioxide is released as a by-product. Phytoplankton respiration also occurs during the day but fortunately for the fish farmer, there is usually a surplus of oxygen produced to compensate for the loss due to respiration. An exception occurs during extended periods of cloud cover. Respiration occurring in the absence of photosynthesis causes oxygen levels to decrease throughout the night. As a result, the lowest concentrations of oxygen are observed immediately prior to sunrise.

Dissolved Gases

Dissolved gases are those which are in a water solution. An example of gas dissolved in solution is soda water which has large quantities of dissolved carbon dioxide. The most common gases are oxygen, carbon dioxide, nitrogen, and ammonia. Concentrations are measured in parts per million (ppm) or milligrams per liter (mg/1), both units of measure are the same. (One ppm or mg/1 is the same as one pound added to 999,999 pounds to total 1,000,000 pounds).

Oxygen

Dissolved oxygen (DO) is by far the most important chemical parameter in aquaculture. **Low-dissolved oxygen levels are responsible for more fish kills, either directly or indirectly, than all other problems combined.** Like humans, fish require oxygen for respiration. The amount of oxygen consumed by the fish is a function of its size, feeding rate, activity level, and temperature. Small fish consume more oxygen than do large fish because of their higher metabolic rate. Meade (1974) determined the oxygen consumption of salmon reared at 57°F was 0.002 pounds per pound of fish per day. Lewis et al. (1981) determined striped bass raised at 77°F consumed 0.012-0.020 pounds per pound of fish per day. The higher oxygen requirement by striped bass may be attributed to the statement that the metabolic rate doubles for each 18°F increase in temperature.

The amount of oxygen that can be dissolved in water decreases at higher temperatures and decreases with increases in altitudes and salinites (Table 1).

Table 1. Solubility of oxygen (ppm) in water at various water temperatures, salinities, and altitudes.

Variable	**Water Temperature °F**				
	68.0	**71.6**	**78.8**	**82.4**	**86.0**
Salinity (ppm)					
0	9.2	8.8	8.2	7.9	7.6
5,000	8.7	8.4	7.8	7.5	7.3
10,000	8.3	8.0	7.4	7.1	6.9
Altitude (ft)					
0 (Sea Level)	9.2	8.8	8.2	7.9	7.6
1,000	8.8	8.5	7.9	7.6	7.4
2,000	8.5	8.2	7.6	7.3	7.1

At sea level and zero salinity 68.0°F water can hold 9.2 ppm, while at 86.0°F, saturation is at 7.6 ppm. In combining this relationship of decreased solubility with increasing temperatures, it can be seen why oxygen depletion are so common in the summer when higher water temperatures occur.

Fish farmer, in an attempt to maximize production, stock greater amounts of fish in a given body of water than found in nature. At times during summer it may be necessary to supply supplemental aeration to maintain adequate levels of dissolved oxygen. Whereas in recirculation systems, the farmer must supply 100 percent of the oxygen needed for the fish and beneficial nitrifying bacteria.

To obtain good growth, fish must be cultured at optimum levels of dissolved oxygen. A good rule of thumb is to maintain DO levels at saturation or at least 5 ppm (Figure 6). Dissolved oxygen levels less than 5 ppm can place undue stress on the fish, and levels less than 2 ppm will result in death (possibly 3 ppm for hybrid striped bass and yellow perch). Some warmwater species such as tilapia and carp are better adapted to withstand occasional low DO levels, while most coolwater species cannot.

Figure 6. General dissolved oxygen requirements in parts per million (ppm) for fish.

Fish are not the only consumers of oxygen in aquaculture systems, bacteria, phytoplankton, and zooplankton consume large quantities of oxygen as well. Decomposition of organic materials (algae, bacteria, and fish wastes) is the single greatest consumer of oxygen in aquaculture systems. Problems encountered from water recirculating systems usually stem from excessive ammonia production in fish wastes. Consumption of oxygen by nitrifying bacteria that break down toxic ammonia to non-toxic forms depends on the amount of ammonia entering the system. Meade (1974) determined that 4.0-4.6 pounds of oxygen are needed to oxidize every pound of ammonia. However, since other bacteria are present in pond and tank culture, a ratio of 6 pounds of oxygen to 1 pound of ammonia is recommended.

Oxygen enters the water primarily through direct diffusion at the air-water interface and through plant photosynthesis. Direct diffusion is relatively insignificant unless there is considerable wind and wave action. Several forms of mechanical aeration are available to the fish farmer. The general categories are:

- Paddlewheels
- Agitators
- Vertical sprayers
- Impellers
- Airlift pumps
- Venturia pumps
- Liquid oxygen injection
- Air diffusers

Mechanical aeration can also increase dissolved oxygen levels. Because of the lack of photosynthesis in indoor water recirculating systems, mechanical means of aeration are the only alternative for supplying oxygen to animals cultured in these systems. Oxygen depletions can be calculated, but predictions can be misleading and should never be substituted for actual measurements.

Carbon Dioxide

Carbon dioxide (CO_2) is commonly found in water from photosynthesis, or in water sources originating from limestone bearing rock. Fish can tolerate concentrations of 10 ppm provided dissolved oxygen concentrations are high. Water supporting good fish populations normally contain less than 5 ppm of free carbon dioxide. In water used for intensive pond fish culture, carbon dioxide levels may fluctuate from 0 ppm in the afternoon to 5-15 ppm at daybreak. While in recirculating systems carbon dioxide levels may regularly exceed 20 ppm, excessively high levels of carbon dioxide (greater than 20 ppm) may interfere with the oxygen utilization by the fish.

There are two common ways to remove free carbon dioxide. First, with well or spring water from limestone bearing rocks, aeration can "blow" off the excess gas. The second option is to add some type of carbonate buffering material such as calcium carbonate ($CaCO_3$) or sodium bicarbonate (Na_2CO_3). Such additions will initially remove all free carbon dioxide and store it in reserve as bicarbonate and carbonate buffers. This concept is discussed in further detail under alkalinity.

Nitrogen

Dissolved gases, especially nitrogen, are usually measured in terms of "percent saturation." Any value greater than the amount of gas the water normally holds at a given temperature constitutes supersaturation. A gas supersaturation level above 110 percent is usually considered problematic.

Gas bubble disease is a symptom of gas supersaturation. The signs of gas bubble disease can vary. Bubbles may reach the heart or brain, and fish die without any visible external signs. Other symptoms may be bubbles just under the surface of the skin, in the eyes, or between the fin rays. Treatment of gas bubble disease involves sufficient aeration to decrease the gas concentration to saturation or below.

Ammonia

Fish excrete ammonia and lesser amounts of urea into the water as wastes. Two forms of ammonia occur in aquaculture systems, ionized and un-ionized. The un-ionized form of ammonia (NH_3) is extremely toxic while the ionized form (NH_4^+) is not. Both forms are grouped together as "total ammonia." Through biological processes, toxic ammonia can be degraded to harmless nitrates (Figure 7).

Figure* 7. *Equation illustrating how toxic un-ionized ammonia (NH_3) is removed from water through the biological process called nitrification.

$$\text{Ammonia } (NH_3) \xrightarrow[\text{Nitrosomons sp.}]{0_2} \text{Nitrites } (N0_2^-) \xrightarrow[\text{Nitrobactor sp.}]{0_2} \text{Nitrates } (N0_3^-)$$

In natural waters, such as lakes, ammonia may never reach dangerous high levels because of the low densities of fish, But the fish farmer must maintain high densities of fish and, therefore, runs the risk of ammonia toxicity. Un-ionized ammonia levels rise as temperature and pH increase (Table 2).

Table 2. Percentage of total ammonia that is un-ionized at various temperatures and pH. To determine un-ionized ammonia concentration, multiply total ammonia concentration by the percentage which is closest to the observed temperature and pH of the water sample. For example, a total ammonia concentration of 5 ppm at pH 9 and 68°F would be: 5 ppm total ammonia X 28.5% = 1.43 ppm.

pH	**54°F**	**62°F**	**68°F**	**75°F**	**82°F**	**90°F**
7.0	0.2	0.3	0.4	0.5	0.7	1.0
7.4	0.5	0.7	1.0	1.3	1.7	2.4
7.8	1.4	1.8	2.5	3.2	4.2	5.7
8.2	3.3	4.5	5.9	7.7	11.0	13.2
8.6	7.9	10.6	13.7	17.3	21.8	27.7
9.0	17.8	22.9	28.5	34.4	41.2	49.0
9.2	35.2	42.7	50.0	56.9	63.8	70.8
9.6	57.7	65.2	71.5	76.8	81.6	85.9
10.0	68.4	74.8	79.9	84.0	87.5	90.6

Toxicity levels for un-ionized ammonia depend on the individual species; however, levels below 0.02 ppm are considered safe. Dangerously high ammonia concentrations are usually limited to water recirculation system or hauling tanks where water is continually recycled and in pond culture after phytoplankton die-offs. However, the intermediate form of ammonia—nitrite—has been known to occur at toxic levels (brown-blood disease) in fish ponds.

Buffering Systems

A buffering system to avoid wide swings in pH is essential in aquaculture. Without some means of storing carbon dioxide released from plant and animal respiration, pH levels may fluctuate in ponds from approximately 4-5 to over 10 during the day. In recirculating systems constant fish respiration can raise carbon dioxide levels high enough to interfere with oxygen intake by fish, in addition to lowering the pH of the water.

pH

The quantity of hydrogen ions (H^+) in water will determine if it is acidic or basic. The scale for measuring the degree of acidity is called the pH scale, which ranges from 1 to 14. A value of 7 is considered neutral, neither acidic or basic; values below 7 are considered acidic; above 7, basic. The acceptable range for fish culture is normally between pH 6.5-9.0.

Alkalinity

Alkalinity is the capacity of water to neutralize acids without an increase in pH. This parameter is a measure of the bases, bicarbonates (HCO_3^-), carbonates (CO_3^{--}) and, in rare instances, hydroxide (OH^-). Total alkalinity is the sum of the carbonate and bicarbonate alkalinities. Some waters may contain only bicarbonate alkalinity and no carbonate alkalinity.

The carbonate buffering system is important to the fish farmer regardless of the production method used. In pond production, where photosynthesis is the primary natural source of oxygen, carbonates and bicarbonates are storage area for surplus carbon dioxide. By storing carbon dioxide in the buffering system, it is never a limiting factor that could reduce photosynthesis, and in turn, reduce oxygen production. Also, by storing carbon dioxide, the buffering system prevents wide daily pH fluctuations.

Without a buffering system, free carbon dioxide will form large amounts of a weak acid (carbonic acid) that may potentially decrease the night-time pH level to 4.5. During peak periods of photosynthesis, most of the free carbon dioxide will be consumed by the phytoplankton and, as a result, drive the pH levels above 10. As discussed, fish grow within a narrow range of pH values and either of the above extremes will be lethal to them.

In recirculating systems where photosynthesis is practically non-existent, a good buffering capacity can prevent excessive buildups of carbon dioxide and lethal decreases in pH. It is recommended that the fish farmer maintain total alkalinity values of **at least** 20 ppm for catfish production. Higher alkalinities of at least 80-100 ppm are suggested for hybrid striped bass. For water supplies that have naturally low alkalinities, agriculture lime can be added to increase the buffering capacity of the water.

Hardness

Water hardness is similar to alkalinity but represents different measurements. Hardness is chiefly a measure of calcium and magnesium, but other ions such as aluminum, iron, manganese, strontium, zinc, and hydrogen ions are also included. When the hardness level is equal to the combined carbonate and bicarbonate alkalinity, it is referred to as carbonate hardness. Hardness values greater than the sum of the carbonate and bicarbonate alkalinity are referred to as non-carbonated hardness. Hardness values of **at least** 20 ppm should be maintained for optimum growth of aquatic organisms. Low hardness levels can be increased with the addition of ground agriculture lime.

Other Metals and Gases

Other metals such as iron and sodium, and gases, such as hydrogen sulfide, may sometimes present special problems to the fish farmer. Most complications arising from these can be prevented by properly pre-treating the water prior to adding it to ponds or tanks. The range of treatments may be as simple as aeration, which removes hydrogen sulfide gas, to the expensive use of iron removal units. Normally iron will precipitate out of solution upon exposure to adequate concentrations of oxygen at a pH greater than 7.0.

Bibliography

Benefield, Larry D., Joseph F. Judkins, and Barron L. Weand. 1982. *Process Chemistry for Water and Wastewater Treatment.* Prentice-Hall, Inc. Englewood, New Jersey. 510 pp.

Boyd, C.E. 1979. *Water Quality in Warmwater Fish Ponds.* Agriculture Experiment Station, Auburn, Alabama. 359 pp.

Brown, E. E., and J. B. Gratzek. 1983. *Fish Farming Handbook: Food, Bait, Tropicals and Goldfish.* AVI Publishing Company, Inc. Westport, Connecticut. 391 pp.

Dupree, Harry K., and Jay V. Huner, editors. 1984. *Third Report to Fish Farmers.* U.S. Fish and Wildlife Service. Washington, D.C. 270 pp.

Lagler, Karl F., John E. Bardach, Robert R. Miller, and Dora R. May Passino. 1977. *Ichthylology.* John Wiley& Sons, Inc. New York. 506 pp.

Lewis, W. M., R.C. Heidinger, and B. L. Tetzlaff. 1981 b. *Tank Culture of Striped Bass.* Fisheries Research Laboratory, Southern Illinois University, Carbondale. 115 pp.

Meade, T. L. 1974. *The Technology of Closed Culture of Salmonids.* University of Rhode Island Marine Technical Report 30. 30 pp.

Reid, George K., and Richard D. Wood. 1976. *Ecology of Inland Waters and Esturaries.* D. Van Nostrand Co. New York. 485 pp.

Rottmann, R.W., and J.V. Shireman. *Management of Water Quality for Fish.* Cooperative Extension Service Circular 715, University of Florida. Gainesville. 18 pp.

Stickney, R. R. 1979. *Principles of Warmwater Aquaculutre*. John Wiley & Sons, Inc. New York. 375 pp.

Swann, LaDon. 1990. *A Basic Overview of Aquaculutre:* AS-457. Purdue University. West Lafayette, Indiana. 10 pp.

Swann, LaDon. 1993. *Water Sources Used in Aquaculture. Illinois-Indiana Sea Grant Program.* AS-486. Purdue University, West Lafayette, IN. 4pp.

Appendix 1

TABLE 3 Suggested water-quality criteria for aquaculture hatcheries or production facilities. Salmonid quality standards with modification for warmwater situations. Concentrations are in ppm (mg/1). (Source: Modification from Wedemeyer, 1977; Piper, etc al. (Larsen), 1982)

Chemical	**Upper Limits for Continuous Exposure and/or Tolerance Ranges**
Ammonia (NH_3)	0.0125 ppm (un-ionized form)
Cadmium[a]	0.004 ppm (soft water < 100 ppm alkalinity)
Cadmium[b]	0.003 ppm (hard water > 100 ppm alkalinity)
Calcium	4.0 to 160 ppm (10.0-160.00 ppm[d])
Carbon dioxide	0.0 to 10 ppm (0.0-15.0 ppm[d])
Cholorine	0.03 ppm
Copper[c]	0.006 in soft water
Hydrogen sulfide	0.002 ppm (Larsen - 0.0 ppm)
Iron (total)	0.0 to 0.15 ppm (0.0-0.5 ppm[d])
Ferrous ion	0.00 ppm
Ferric ion	0.5 ppm (0.0-0.5 ppm[d])
Lead	0.03 ppm
Magnesium	(Needed for buffer system)
Manganese	0.0 to 0.01 ppm
Mercury (organic of inorganic)	0.002 ppm maximum, 0.00005 ppm average
Nitrate (NO^{-}_3)	0.0 to 3.0 ppm
Nitrite (NO^{-}_2)	0.1 ppm in soft water, 0.2 ppm in hard water 0.03 and 0.06 ppm nitrite-nitrogen
Nitrogen	Maximum total gas pressure 110% of saturation
Oxygen	5.0 ppm to saturation; 7.0 to saturation for eggs or broodstock
Ozone	0.005 ppm
pH	6.5 to 8.0 (6.6-9.0[d])
Phosphorus	0.01 to 3.0 ppm
Polychlorinated biphenyls (PCBs)	0.002
Total suspended and settleable solids	80.0 ppm or less
Total Alkalinity (as $CaCO_3$)	10.0 to 400 ppm (50.0-4.00.0 ppm[d])
% as phenolphthalein	0.0 to 25 ppm (0.40 ppm[d])
% as methyl orange	75 to 100 ppm (60.0-100.0 ppm[d])
% as ppm hydroxide	0.0 ppm
% as ppm carbonate	0.0 to 25 ppm (0.0-40.0 ppm[d])
% as ppm bicarbonate	75 to 100 ppm
Total Hardness (as $CaCO_3$)	10 to 400 ppm (50.0-400.0 ppm[d])
Zinc	0.03-0.05 ppm

---

[a] To protect salmonid eggs and fry. For non-salmonids 0.004 ppm is acceptable

[b] To protect salmonid eggs and fry. For non-salmonids 0.03 ppm is acceptable

[c] Copper at 0.005 ppm may suppress gill adensione triphosphatase and compromise smoltification in anadromous salmonids.

[d] Warm water situations

Printed on
Recycled Paper

PRINTED WITH SOY INK

NA 89AA-D-SG058 REV 3/97